TABLE 1.—*Comparison of minimum temperature observations at Belle Chasse, La., and 2 additional ground-level stations, with the minimum at New Orleans Weather Bureau office as the basis for comparison, on 14 dates when Belle Chasse was 20° or more below New Orleans*

Date	Minimum temperature, New Orleans	Belle Chasse		Delta Farms		Houma	
		Minimum	Difference	Minimum	Difference	Minimum	Difference
	°	°	°	°	°	°	°
Nov. 30, 1935	49	29	20	?	-------	36	13
Oct. 19, 1936	64	43	21	?	-------	49	15
Dec. 23, 1936	50	26	24	?	-------	33	17
Mar. 19, 1938	68	45	23	?	-------	57	11
Oct. 25, 1938	55	32	23	36	19	39	16
Oct. 26, 1938	55	34	21	36	19	40	15
Oct. 29, 1938	59	39	20	44	15	43	16
Oct. 30, 1938	60	38	22	44	16	42	18
Nov. 10, 1938	48	26	22	34	14	32	16
Nov. 21, 1938	52	31	21	36	16	36	16
Nov. 29, 1938	40	16	24	23	17	24	16
Nov. 30, 1938	43	18	25	24	19	27	16
Dec. 6, 1938	47	23	24	29	18	32	15
Jan. 20, 1939	47	27	20	?	-------	29	18
Average depression of minimum below New Orleans	-------	-------	22	-------	17	-------	16

TABLE 2.—*Tabulation of daily differences in minimum temperature at Belle Chasse compared with those at the Weather Bureau Office in New Orleans. (All temperatures at Belle Chasse are lower than those with which they are compared.) Based on 44 months of record; 1935–39*

Month	Average monthly depression of minima at Belle Chasse	Percentage of daily observations with the minimum temperature at Belle Chasse—		
		10° or more below New Orleans	15° or more below New Orleans	20° or more below New Orleans
	°F.	*Percent*	*Percent*	*Percent*
January	4	16	5	1
February	4	17	0	0
March	7	35	16	1
April	7	37	8	0
May	7	45	5	0
June	8	33	1	0
July	6	12	0	0
August	7	18	0	0
September	7	28	5	0
October	9	42	19	5
November	8	37	22	4
December	7	34	18	4
Annual average	7.6	30	8	1

RADIATIVE COOLING IN THE LOWER ATMOSPHERE

By WALTER M. ELSASSER

[California Institute of Technology and U. S. Weather Bureau, August 1940]

The writer has recently developed a graphical method for the determination of radiative heat transfer in the atmosphere (1). This is a modification of the graphical method introduced some years ago by Mügge and Möller (2). In this method moisture and temperature values of a given atmosphere are plotted on a printed diagram (later referred to as Radiation Chart) and the radiative flux at any level can be obtained by evaluating an area on the chart. The results given below represent the first practical tests of our chart. A comprehensive paper covering the theory of the chart has just been published (1) and we shall therefore omit references to the theoretical foundations of this work and confine ourselves to a communication of the results.*

I. FREE AIR COOLING

We used airplane observations of free air moistures and temperatures. The stations selected (with the exception of Fort Smith, Northwest Territory) are located in two north-south cross sections over the United States. The mean values of February 1937 and of August 1937 served as basis for these calculations. The cooling calculated represents the mean cooling in layers 1 kilometer thick due to the long-wave radiation of water vapor (the cooling due to carbon-dioxide radiation is found negligible). The procedure of evaluating the cooling was as follows. First, specific humidity (with a pressure correction applied, see below) was plotted against pressure. The points were joined by a curve and the total amount of moisture between successive levels, 1 kilometer distant, was determined by means of a planimeter. These values of total moisture were then plotted against temperature on the radiation chart. It is usually possible to plot, on the same chart, curves corresponding to several or to all levels of one station. The area contained between curves representing successive levels measures the heat loss of the layer between them; this loss divided by the heat capacity of the layer gives the net cooling.

*Part of the calculations was carried out by A. C. Gibson of the U. S. Weather Bureau, now at Jacksonville, Fla.

There is still a certain doubt about the manner in which the air pressure affects the radiative properties of water vapor. According to a theoretical formula (3) the absorption should be proportional to the pressure, while F. Schnaidt (4) derives from measurements of G. Falckenberg (5) the result that the absorption is proportional to the square root of the air pressure. The latter view is sustained by other, yet unpublished, experiments carried out by John Strong at the California Institute of Technology. We therefore used the square root pressure correction in our computations.

The figures in table 1 represent mean values of the cooling in layers 1 kilometer thick. It is to be understood that these layers have nothing to do with the division of the atmosphere in layers in the manner of Simpson (6). The latter division originates from a method of approximation where differentials are replaced by finite differences. Our figures, on the other hand, represent rigorous solutions of the differential equations of radiative transfer, once the absorption coefficients of water vapor are given. It would be possible to calculate the "local" cooling at any given level, but the determination of the mean cooling of a layer of reasonable thickness is less laborious and also much more accurate. The values given in table 1 are in degrees centigrade per day.

All the cooling values contained in table 1 are plotted in figure 1 with the decadic logarithm of the specific humidity as abscissa. The oblique line represents the empirical relation

$$(\Delta T)_{day} = 1 + 2 \log_{10} w \qquad (1)$$

The two dashed lines are set off from the main line by 0.4° on each side. It is seen that the large majority of the points falls within these boundaries. The major deviations seem to occur in the lowest kilometer; the points representing these layers are indicated by rings in figure 1. The cause of this decrease in cooling is presumably to be found in the relatively lower mean temperature of the lowest kilometer due to the influence of the nocturnal ground inversion. Caution should therefore be used in the application of formula (1) to meteorological problems. We think, however, that (1) is a workable approximation for average conditions in middle latitudes and in the lower middle troposphere. It should not be extrapolated to other conditions without new checks by direct application of the chart.

II. CLOUD COOLING

If the curves representing the moisture-temperature relations are drawn on the radiation chart, it is easy to determine the amount of heat which a black surface located at any level of the atmosphere gains or loses if it radiates upward or downward. As the base and the top of a cloud represent such black surfaces one can readily obtain the mean cooling of a cloud. There is usually a gain of heat at the base and a loss at the top of a cloud, the latter being by far the larger. In table 2 figures representing the gain at a cloud base and the loss at a cloud top located at the levels indicated are given in calories per 3 hours.

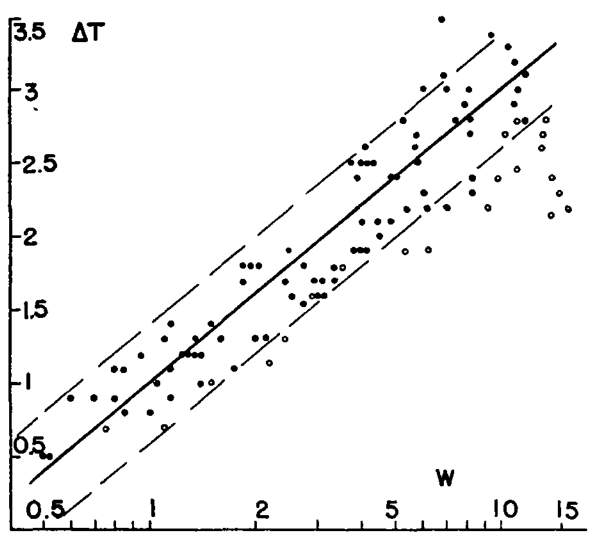

FIGURE 1.

It is seen that the net loss for a cloud of 1 kilometer thickness runs very near to 30 calories per 3 hours; only for clouds in the lowest kilometer the values are somewhat lower. The following formula gives a fairly good estimate of the cooling of a cloud under average conditions:

$$(\Delta T)_{day}=\frac{1{,}000}{d} \tag{2}$$

Here d is the thickness of the cloud expressed in millibars and the cooling is given in degrees centigrade per day. Formula (2) applies under about the same conditions and the same restrictions as fomula (1) for the free-air cooling.

It must be said here that the moisture distribution in the mean soundings is of course such that no clouds would be expected, as the relative humidity nowhere reaches 100 percent. Our calculations show, however, that the cooling values are rather insensitive to small changes in moisture and the values in table 2 would therefore only change by a few percent if in place of the mean soundings we substituted soundings in which the humidity actually goes up to 100 percent at the cloud. A similar argument may also be applied to the free-air cooling as given in Table 1. If we wanted to obtain the actual mean cooling, we would have to use the mean of only those soundings which correspond to a cloudless sky. As this would not be very different from the over-all monthly mean, we introduce only a small error by using the latter throughout our calculations.

Table 3 contains the values of the heat loss at the ground for a cloudless sky computed in the same manner.

III. RADIATIVE HEAT TRANSFER IN NOCTURNAL GROUND INVERSIONS

In the calculations for table 1 it was assumed *that the ground itself has the same temperature as the air near the ground* whose temperature is indicated in the soundings. Actually, during the night the ground temperature will sink below that of the air in the lowest layers and this phenomenon will intensify the formation of ground inversions. Calculations which give the order of magnitude of this effect are summarized in table 4. It was found convenient to calculate for a number of typical cases rather than for selected individual records. The first two lines of table 4 give the temperatures and specific humidities in the air near the ground for which the calculations were carried through. Assume for a moment that the ground and a layer of air have the same temperature. A certain amount R of radiation emitted by the ground is absorbed by the air near the ground. If there is a temperature difference between the two radiations, a net flux of heat

$$F=\delta T\frac{dR}{dt}$$

will take place. The quantity dR/dT can be obtained from the chart (it is equal to the area of a strip bounded by 2 isotherms distant by 1° and by 2 moisture isopleths which correspond to the bottom and to the top of the layer). Since the layers are rather thin, it is necessary to calculate also the heat flux due to the radiation in the carbon-dioxide band. Schnaidt (4) gives a curve for the absorption of CO_2 radiation as function of the thickness. The experimental data were corrected by him so that this final curve refers to a condition where both the emitting black body and the absorbing layers are at the same temperature of 0° C. According to Schnaidt, about 8 percent of the total radiation of a black body of 0° C. is absorbed by the CO_2 in the first 100 m. of air and about 6 percent more by the CO_2 in the next following 300 m., while beyond this distance there is very little additional absorption. These figures refer to the absorption of a straight beam; the corresponding values for diffuse radiation are obtained approximately by taking half the thicknesses for the same percentual absorption. Let R' be the amount of radiation in the CO_2 band which is exchanged between the ground and any layer of air of the same temperature as the ground; further, put $R'=a\,I'$ where I' is the spectral intensity of black body radiation at the center of the CO_2 band and a a numerical factor. We have then for the heat transfer due to carbon-dioxide radiation

$$F=\delta T\frac{dR'}{dT}=\delta T\cdot a\frac{dT'}{dT}=\delta T\frac{R'}{I'}\cdot\frac{dT'}{dT}$$

Now the quantity $dI'/I'\,dT$ can immediately be calculated from Planck's law while R' is given by the figures quoted above. We now calculate the net cooling of the air which will be

$$\text{Cooling}=\frac{\delta T}{C}\left(\frac{dR}{dT}+\frac{R'}{T'}\frac{dT'}{dT}\right) \tag{3}$$

where C is the heat capacity of the layer. We assume that the layer is homogeneous in temperature; then δT represents the difference between the temperature of the layer and that of the ground. The numerical results obtained from formula (3) for various temperatures and corresponding moistures are summarized in table 4. The values given in the last two lines are the values of the factor of δT in (3); multiplied by δT they give the actual cooling in these layers in an interval of three hours. The same figures can of course also be applied to compute the radiative part of the heating of the air near the ground during the day when the ground temperature is higher than the air temperature.

The results contained in table 4 indicate that radiative exchange of heat between the ground and the atmosphere is concentrated in the lowest 50 meters and is very small above this height. The observed ground inversions are often of the order of 1 kilometer and if the total heat exchange for both layers (which is between 0.3 and 0.5 calorie per degree temperature difference of air and ground) is distributed over the height of the inversion, the resulting decrease in temperature is extremely small. Only during the polar night where the ground temperature can fall much below the temperature of the air, does this mechanism of radiative transfer produce an appreciable effect, as has been pointed out by Wexler (**8**). We must conclude that the ordinary nocturnal inversion is almost exclusively of turbulent origin so far as the transfer of heat from the ground to the air is concerned. It is of course of radiative origin in the sense that the heat loss of the ground itself is of a purely radiative nature.

IV. CONCLUSIONS

The results given above show that the radiative cooling in the free air and in absence of clouds is confined within rather narrow limits. Roughly, it is of the order of 1° per day in air masses of polar type and of the order of 2° to 3° per day in air masses of equatorial type. Furthermore, it appears clearly that there is no indication of a heating of the atmosphere by radiation. *With regard to long-wave radiation the atmosphere is a cold source throughout.* This result has already been reached by Mügge and Möller (**2**) and by Albrecht (**9**). Apart from the heat of condensation, all the heat lost by radiation of the atmosphere must therefore be supplied by turbulent exchange and by convection (frontal, cyclonic, and local). It may appear rather surprising at first sight that the lapse rate in the free atmosphere is not much more frequently superadiabatic and that local convection does not play a much larger role than is actually observed. In this connection we might notice, however, that the rate of cooling above 2 kilometers decreases steadily with height and we might presume that this decrease continues beyond 5 kilometers, where our calculations end. In the course of several days this must lead to an appreciable stabilization of the lapse rate in the middle troposphere. Since radiative cooling acts continuously everywhere, it probably constitutes also itself the major stabilizing factor in the atmosphere.

The work on the radiation chart referred to above, and the present investigation, were carried out with financial assistance from the Bankhead-Jones research fund of the United States Department of Agriculture.

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TABLE 1.—*Cooling of 1-km. layers in ° C. per day for cloudless sky—monthly means*

Station, month	Grd.	1 km.	2 km.	3 km.	4 km.	5 km.
Fort Smith, Northwest Territory, February 1937:						
Temperature	−23.3	−16.1	−16.7	−21.4	−26.6	—
Specific humidity	.6	.9	.8	.6	.4	—
Cooling	0.7	1.1	0.9	0.5	—	
Fargo, N. Dak., February 1937:						
Temperature	−16.5	−11.0	−11.0	−14.9	−20.6	−26.8
Specific humidity	.8	1.4	1.3	1.0	.6	.4
Cooling	0.7	1.3	1.4	1.1	0.5	
Omaha, Nebr., February 1937:						
Temperature	−7.3	−6.0	−6.8	−10.9	−16.3	−22.9
Specific humidity	1.8	1.9	1.6	1.3	.9	.6
Cooling	1.0	0.8	1.3	1.2	1.1	
Oklahoma City, Okla., February 1937:						
Temperature	.9	2.8	1.6	−3.8	−9.5	−16.0
Specific humidity	3.0	2.8	2.1	1.6	1.1	.8
Cooling	1.6	1.7	1.7	1.2	1.2	
San Antonio, Tex., February 1937:						
Temperature	7.8	10.2	8.2	3.9	−2.0	−8.2
Specific humidity	5.2	5.4	4.4	3.2	2.3	1.6
Cooling	1.9	2.4	1.9	1.8	1.8	
Sault Ste. Marie, Mich., February 1937:						
Temperature	−10.1	−9.5	−11.9	−15.6	−21.0	−27.4
Specific humidity	1.4	1.6	1.2	1.0	.7	.5
Cooling	1.0	1.0	1.3	0.8	0.9	
Detroit, February 1937:						
Temperature	−3.6	−4.4	−6.7	−10.9	−16.1	−21.9
Specific humidity	2.3	2.1	1.4	1.2	.9	.7
Cooling	1.2	1.1	1.2	1.0	0.9	
Dayton, Ohio, February 1937:						
Temperature	−2.4	−2.9	−4.6	−8.7	−13.8	−19.8
Specific humidity	2.5	2.4	1.6	1.2	1.1	.9
Cooling	1.3	1.3	1.2	0.9	0.8	
Nashville, Tenn., February 1937:						
Temperature	4.6	2.6	−.1	−4.4	−9.4	−15.1
Specific humidity	3.8	3.3	2.4	1.7	1.3	1.0
Cooling	1.8	1.6	1.8	1.4	1.1	
Montgomery, Ala., February 1937:						
Temperature	7.5	5.9	2.6	−.4	−5.2	−10.9
Specific humidity	4.4	3.3	2.6	1.7	1.5	1.0
Cooling	1.9	1.7	1.3	1.3	1.2	
Pensacola, Fla., February 1937:						
Temperature	8.7	9.1	5.7	2.1	−3.3	−8.8
Specific humidity	6.4	6.0	4.8	3.2	2.1	1.6
Cooling	1.9	2.2	2.1	1.6	1.8	
Miami, Fla., February 1937:						
Temperature	16.3	14.8	11.3	6.0	1.0	−4.0
Specific humidity	9.8	8.6	5.4	4.3	3.4	2.7
Cooling	2.2	2.2	2.1	1.9	1.6	
Fargo, N. Dak., August 1937:						
Temperature	18.9	22.2	17.5	10.8	4.1	−3.1
Specific humidity	11.3	9.3	6.7	4.7	3.5	2.7
Cooling	2.7	3.0	2.6	2.6	1.7	
Omaha, Nebr., August 1937:						
Temperature	23.1	24.7	19.5	12.6	6.0	−.7
Specific humidity	14.4	12.4	9.2	7.2	4.8	3.2
Cooling	2.8	3.2	2.8	3.0	2.5	
Oklahoma City, Okla., August 1937:						
Temperature	24.6	26.3	19.6	11.9	5.0	−1.8
Specific humidity	14.7	12.8	10.7	8.1	5.4	3.1
Cooling	2.7	3.1	3.4	3.5	2.5	
San Antonio, Tex., August 1937:						
Temperature	25.2	23.7	16.9	10.3	4.2	−1.0
Specific humidity	15.7	12.2	9.6	6.1	4.0	2.7
Cooling	2.4	2.9	2.8	2.4	1.7	
Sault Ste. Marie, Mich., August 1937:						
Temperature	16.1	18.2	13.5	8.1	2.2	−4.1
Specific humidity	10.4	9.2	7.0	4.5	3.0	2.0
Cooling	2.4	3.0	2.7	2.5	1.9	
Detroit, August 1937:						
Temperature	19.6	19.5	13.6	8.3	2.6	−3.2
Specific humidity	12.8	9.4	7.0	4.6	3.2	2.3
Cooling	2.8	2.7	2.5	2.4	1.8	
Dayton, Ohio, August 1937:						
Temperature	19.2	21.5	15.3	10.2	4.4	−1.4
Specific humidity	13.0	12.1	8.7	5.0	3.3	2.2
Cooling	2.6	3.3	3.1	2.5	1.6	
Nashville, Tenn., August 1937:						
Temperature	22.8	21.9	15.5	9.3	3.9	−1.6
Specific humidity	14.6	13.0	9.4	6.4	4.1	2.6
Cooling	2.2	3.0	2.9	2.8	1.8	

TABLE 1.—*Cooling of 1-km. layers in ° C. per day for cloudless sky—monthly means*—Continued

Station, month	Grd.	1 km.	2 km.	3 km.	4 km.	5 km.
Montgomery, Ala., August 1937:						
Temperature	24.5	21.2	14.7	8.9	3.3	−1.7
Specific humidity	16.7	12.8	9.5	7.0	5.3	3.7
Cooling		2.3	2.4	2.3	2.2	2.0
Pensacola, Fla., August 1937:						
Temperature	23.8	20.8	15.1	9.4	3.8	−1.4
Specific humidity	17.2	13.8	9.7	6.9	5.2	3.7
Cooling		2.2	2.8	2.4	2.3	2.1

TABLE 2.—*Heat gain at cloud base and heat loss at cloud top in calories per cm² per 3 hours—same mean monthly soundings as table 1*

Station	1 km.	2 km.	3 km.	4 km.	5 km.
Fort Smith, Northwest Territory: February 1937:					
Gain base	−4.0	−3.2	−0.2	2.4	....
Loss top	29.0	31.8	31.1	30.7	....
Fargo, N. Dak.:					
February 1937:					
Gain base	−3.3	−3.0	−.6	3.6	7.4
Loss top	29.3	33.2	33.9	33.6	31.6
August 1937:					
Gain base	−2.3	1.6	5.9	10.1	14.3
Loss top	27.7	32.8	35.8	37.9	37.6
Omaha, Nebr.:					
February 1937:					
Gain base	−1.0	−.2	2.4	5.0	9.8
Loss top	21.1	33.0	33.9	33.3	32.1
August 1937:					
Gain base	−1.0	2.9	6.8	10.5	14.5
Loss top	24.2	29.8	33.7	36.8	37.9
Oklahoma City, Okla.:					
February 1937:					
Gain base	−1.3	−.1	3.8	7.3	11.4
Loss top	32.2	36.8	38.9	37.3	36.1
August 1937:					
Gain base	−1.0	3.6	7.4	11.4	14.8
Loss top	23.8	28.7	33.2	38.5	40.5
San Antonio, Tex.:					
February 1937:					
Gain base	−2.1	.3	3.0	7.0	10.9
Loss top	28.6	33.6	37.3	33.5	37.6
August 1937:					
Gain base	1.0	5.1	8.6	11.9	14.6
Loss top	25.0	29.8	33.9	37.9	39.4
Sault Ste. Marie, Mich.:					
February 1937:					
Gain base	−.3	1.1	3.5	6.8	10.4
Loss top	30.1	32.1	33.0	32.0	30.5
August 1937:					
Gain base	−1.4	2.3	5.6	8.9	12.9
Loss top	26.3	31.7	34.7	37.7	37.9
Detroit:					
February 1937:					
Gain base	.5	1.9	4.4	7.6	11.0
Loss top	30.1	32.1	33.0	32.0	30.5
August 1937:					
Gain base	0	4.0	7.1	10.1	13.5
Loss top	26.6	31.0	35.0	37.7	38.4
Dayton, Ohio:					
February 1937:					
Gain base	.3	1.4	4.0	7.2	10.6
Loss top	29.9	33.2	34.2	33.3	31.7
August 1937:					
Gain base	−1.6	2.8	5.8	9.4	13.0
Loss top	25.5	31.4	36.5	39.3	41.4
Nashville, Tenn.:					
February 1937:					
Gain base	1.3	3.1	5.9	8.7	12.2
Loss top	30.9	34.8	35.7	36.0	35.5
August 1937:					
Gain base	.8	4.5	7.9	10.7	13.5
Loss top	23.3	28.7	33.3	37.5	38.6
Montgomery, Ala.:					
February 1937:					
Gain base	1.0	3.3	5.2	8.0	11.7
Loss top	31.7	35.0	37.3	37.6	36.7
August 1937:					
Gain base	2.0	5.6	8.4	10.8	13.2
Loss top	22.9	27.0	30.9	34.2	36.3

TABLE 2.—*Heat gain at cloud base and heat loss at cloud top in calories per cm² per 3 hours—same mean monthly soundings as table 1*—Con.

Station	1 km.	2 km.	3 km.	4 km.	5 km.
Pensacola, Fla.:					
February 1937:					
Gain base	−.2	2.1	4.5	7.7	10.2
Loss top	26.7	31.2	34.8	35.3	37.1
August 1937:					
Gain base	1.6	4.6	7.7	10.2	12.7
Loss top	21.7	26.4	30.2	33.5	35.8
Miami, Fla.: February 1937:					
Gain base	.9	3.6	6.3	9.3	11.9
Loss top	26.0	30.7	33.1	34.9	38.0

TABLE 3.—*Nocturnal heat loss of the ground in calories per cm² per 3 hours for cloudless sky—based on same mean soundings as above*

Fort Smith, February	22.8
Fargo:	
February	24.0
August	19.1
Omaha:	
February	27.3
August	18.0
Oklahoma City:	
February	27.5
August	17.9
San Antonio:	
February	21.4
August	18.8
Sault Ste. Marie:	
February	28.8
August	18.6
Detroit:	
February	26.8
August	19.6
Dayton:	
February	26.5
August	17.4
Nashville:	
February	26.9
August	18.2
Montgomery:	
February	26.5
August	18.3
Pensacola:	
February	19.7
August	15.9
Miami:	
February	19.3

TABLE 4.—*Differential radiative cooling of lowest strata per degree temperature difference between the layer and the ground—add to free cooling values of table 1*

Temperature / Specific humidity } assumed	−20° / 1	−10° / 2	0° / 3	+10° / 6	+20° / 10
0–50 m.					
Water, cal./cm.²/3 hr	12.0	15.9	20.5	27.6	$35.9\cdot10^{-3}$
CO_2, cal./cm.²/3 hr	9.8	9.2	8.6	7.9	$7.3\cdot10^{-3}$
50–200 m.					
Water, cal./cm.²/3 hr	4.3	5.5	6.5	7.9	$10.5\cdot10^{-3}$
CO_2, cal./cm.²/3 hr	7.4	6.9	6.4	5.9	$5.5\cdot10^{-3}$
Differential cooling in °C. per 3 hours					
0–50 m	.13	.16	.19	.24	.30
50–200 m	.023	.025	.027	.030	.036